Proceedings of the 4th International Conference on Mechatronics and Smart Systems
DOI: 10.54254/2755-2721/2026.33940

Research Progress in Global Marine Energy Power Generation Technology

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Abstract. As a critical pathway to promote the global energy transition, marine energy power generation faces challenges in achieving full commercialization currently. To clarify its technological development trajectory and breakthrough directions, by reviewing and analyzing authoritative academic literature and industry reports, this paper systematically analyzes the technology spectrum, key technological breakthroughs, integration challenges and future trends. The review indicates that research on tidal and wave energy has been relative maturity, with related studies shifting to a model-driven approach based on high-fidelity simulation and land-sea validation. At the system level, energy smoothing and intelligent grid connection technology has solved the problem of grid compatibility, while the high-resilience deployment and predictive operation and maintenance system provides a solution for the economic development of deep-sea projects. This study points out that the core competition in marine energy technology has shifted from individual machines to system engineering capabilities. And that can provide guidance for subsequent research focus, engineering practice optimization, and industrial policy formulation in the field.

Keywords: Ocean energy power generation, System integration, Deep-sea deploy, Artificial intelligence for IT operations

1. Introduction

Driven by carbon peaking and carbon neutrality goals, the global energy structure is gradually transitioning. As a "treasure trove of resource", the marine contains vast reserves of marine energy. Therefore, the development and commercial utilization of marine energy have become research emphasis and strategic direction in the global energy sector.

The large-scale development and utilization of marine energy has been linked to technological advancement for a long time, but now its research paradigm has shifted fundamentally.Early research (prior to around 2010) primarily focused on the feasibility and the verification of diverse prototypes, showing a "blooming of various approaches": scholars devoted to exploring various energy conversion pathways, such as oscillating water column (OWC), raft-type, and point absorption type wave energy devices and horizontal-axis and vertical-axis tidal current turbines. Most projects just involved single demonstration units at the hundred-kilowatt scale, aimed at verifying feasibility in real environments, while discussions on commercial prospects largely remained theoretical.

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DOI: 10.54254/2755-2721/2026.33940

But in the past decade the research frontier has take a fundamental shift. And it is driven by clear commercialization objectives rather than mere principle exploration. Firstly, a shift in research scale is it changes from single devices to clusters. So the core issues are no longer the peak efficiency of individual devices but the engineering reliability of megawatt-scale units, wake effects in array layouts, and the economic viability of operation and maintenance over the full life cycle. Second, technological pathways are converging by competition. Numerous early technological routes have undergone natural selection in harsh marine environments and technologies like tidal current energy have stabilized relatively. At the same time, the deep integration of cross-disciplinary technologies such as new materials, intelligent control and predictive operation and maintenance is addressing core bottlenecks in commercialization,including durability, efficiency, and cost systematically.

Based on the above analysis,this paper first analyzes the strategic significance of ocean energy power generation in the process of global energy transition. And then explains the principles of various ocean energy power generation technologies such as wave and tidal energy. Subsequently, the breakthroughs of key technologies will be emphatically analyzed, especially the application of high-precision modeling tools, real-sea environment testing and verification technologies and the improvement of material properties and anti-corrosion technologies in optimizing the reliability and performance of equipment. Finally, combined with the development trend of technologies, prospects are made for emerging fields such as intelligent design and energy complementation. This research aims to offer a clear technology roadmap for academia and industry to understand the frontiers of marine energy power generation and overcome key technological bottlenecks.

2. Technology lineage and operating principle

Marine energy technologies encompass a vast and complex spectrum. Their classification is primarily based on the source of energy,categorized into celestial gravitational energy, solar radiation energy, and geophysical chemical energy,and the principle of energy conversion,categorized into mechanical, thermal, and chemical energy. By integrating these, the international community classifies marine energy into the following five main types typically: tidal energy, wave energy, tidal current energy, marine thermal energy, and salinity gradient energy. A profound understanding of the conversion principles of different energy sources is fundamental to assessing their technological status and potential.

As shown in Table 1, tidal current energy and wave energy have entered a demonstrating and early commercial phase. That was supported by long-term, real-sea operational data from sites such as the UK's European Marine Energy Centre (EMEC) test site and China's LHD power station. Tidal range energy utilizing barrage structures has achieved commercialization, even it is limited by geographical constraints. In contrast, marine thermal energy and salinity gradient energy remain in the stages of technological R&D and demonstration and they represent more frontier and conceptual technologies. This landscape determines the current R&D focus is twofold: firstly, addressing system integration challenges based on relatively mature power generation devices, and second, pioneering novel technologies to explore innovative pathways.

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Table 1. Comparison of five marine energy power generation technologies

Technology Type	Energy Source & Form	Primary Conversion Principle	Typical Technological Pathways	Maturity Level
Wave Energy	Solar Energy (indirect); Mechanical Energy	Captures wave motion energy to drive mechanical or hydraulic systems.	Oscillating Water Column (OWC), Point Absorber, etc.	Demonstration & Pre-commercial
Tidal Current Energy	Celestial Gravitational Energy; Mechanical Energy (Kinetic)	Utilizes water flow to drive underwater turbines.	Horizontal-Axis Turbines, Vertical-Axis Turbines	Demonstration & Early Commercial
Tidal Range Energy	Celestial Gravitational Energy; Mechanical Energy (Potential)	Utilizes tidal height differential to drive hydro turbines.	Barrage, Tidal Lagoon	Commercial (Selected Projects)
Ocean Thermal Energy	Solar Energy; Thermal Energy	Utilizes seawater temperature gradient to drive thermodynamic cycles.	Open-Cycle, Closed-Cycle, Hybrid-Cycle	Research & Demonstration
Salinity Gradient Energy	Chemical Potential Energy; Chemical Energy	Utilizes osmotic pressure or electrical potential generated by salinity difference.	Pressure Retarded Osmosis (PRO), Reverse Electrodialysis (RED	Early R&D Stage

3. Key technological advances: from simulation to system verification

Nowadays, the research and development of marine energy technology has entered a new paradigm called model-driven, integrated land-sea development. Its core is, before prototype manufacturing, completing performance prediction and optimization as much as possible through high-precision numerical simulation and systematic experimental verification, so significantly reducing R&D costs and risks while accelerating the pace of technological iteration.

3.1. High-fidelity numerical simulation and performance prediction

Computational Fluid Dynamics (CFD) and multi-body dynamics simulation have become core virtual test platforms for the design and optimization of marine energy devices [1], covering from conceptual design and detailed engineering to performance prediction.

Specifically in refined flow field analysis and load prediction, the Reynolds-Averaged Navier–Stokes (RANS) solver is widely adopted in the industry [2, 3] to simulate the flow characteristics of tidal current turbines. Combined with sliding mesh technology, it can reproduce the transient hydrodynamic behavior of rotors under complex inflow conditions. By using advanced turbulence models such as the SST k-ω model, flow separation and pressure distribution on blade surfaces can be predicted more accurately, enabling precise calculation of the critical power coefficient and thrust load spectrum [4]. Simulation strategies for wave energy converters differ slightly; the potential flow theory is usually combined with viscous CFD to balance computational efficiency and accuracy.

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The current research frontier also shifts from single-domain hydrodynamic analysis to strongly coupled multi-physics research, integrating hydrodynamics, structural mechanics and control systems [5]. For instance, Fluid-Structure Interaction (FSI) analysis is applied to study the elastic deformation of blades caused by hydrodynamic loads and its feedback effect on hydrodynamic performance. Meanwhile, by embedding control system models into the simulation loop, engineers can test and optimize control strategies like Maximum Power Point Tracking (MPPT) in a virtual environment. Furthermore, to capture more complex transient physical phenomena, researchers are employing more computationally intensive methods such as Large Eddy Simulation (LES) to investigate key issues including transient cavitation and vortex-induced vibration [6].

3.2. Systematic experimental verification system: from laboratory to real-sea conditions

Although numerical simulation provides valuable insights, it must be verified and calibrated through systematic physical experiments to form a closed simulation–testing loop which is essential for ensuring technical reliability.

The research and development process begins with laboratory-scale model testing. Scale model tests conducted in controlled environments such as towing tanks and wave basins are critical in the early R&D stage. Following similarity criteria including the Froude number, these tests are mainly used to calibrate numerical models, evaluate the feasibility of conceptual designs, and optimize power take-off systems and control algorithms, thus preliminarily verifying the basic viability of technical schemes.

Subsequently offshore prototype testing and performance evaluation are carried out. Professional offshore test sites like the European Marine Energy Centre (EMEC) in Scotland and PacWave in the United States established worldwide and provide full-scale prototypes with rigorous testing under real ocean conditions. Unlike laboratory tests, this stage focuses entirely on long-term quantitative assessment of reliability, maintainability and survivability. For example, long-term monitoring of the LHD tidal current power station deployed in the Zhoushan Sea, Zhejiang Province, China, has yielded key operational data under extreme sea conditions, wear conditions of critical components and core performance indicators such as annual power generation and availability. Such long-term real-world data is invaluable for validating simulation models, identifying failure modes, and ultimately evaluating the commercial feasibility of the technology.

4. System integration technologies

The success of individual devices is only the first step. Their safe, reliable, and cost-effective integration into the energy system are more complex. Two of the core challenges are the intermittent and stochastic characteristics of the power output and the engineering and operational difficulties arising from deep-sea and distant-sea environments.

4.1. Power smoothing and grid integration technologies

Marine energy, particularly wave energy, exhibits strong intermittency and stochasticity in its power output, which poses significant challenges to grid stability.To address this issue, there are two core technologies called power smoothing and grid-connected inverter technologies.

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4.1.1. Power smoothing technology

Power smoothing technology means addresses power fluctuations by integrating an energy storage system, such as hydraulic accumulators, supercapacitors, or battery energy storage systems between the wave energy device and the power grid. Energy storage elements absorb the peak power and release energy to fill the power valleys and then delivering smoothed power.

To optimize this, short-term power forecasting technology based on AI are rising. For instance, based on a CNN-BiLSTM-DELA model, Zhang Yuxiang et al. [7] proposed a wave energy forecasting technique, which can predict power fluctuations beforehand. This can guide the charging and discharging of energy storage equipment, enhances the power smoothing effect, and extends the storage devices's service life.

4.1.2. Grid-connected inverter technology

As the core equipment, the grid-connected inverter ensures the stable and efficient interface between marine energy generation systems and the power grid. It is responsible for converting the preliminarily smoothed DC or variable-frequency AC power into high-quality AC power that strictly complies with grid standards. In medium and high-power application scenarios, the modular multistage converter (MMC) with a three-level topology ,owing to its outstanding output waveform quality and energy efficiency performance, has emerged as a focal technology in high-voltage and high-capacity applications.

Through intelligent control algorithms like virtual synchronous generator (VSG) technology, the grid-connected inverter can provide essential inertial support for weak grids and then enhance the grid stability. Meanwhile, its low-voltage ride-through (LVRT) capability ensures the inverter maintains operation and assists in voltage recovery during grid faults, which is important for maintaining the overall stable operation of power system.

4.2. Deep-sea deployment and intelligent operation and maintenance

To access higher-quality resources, marine energy development is advancing into more distant seas. The deep-sea environment, characterized by extremely low velocities, complex and variable flow directions and harsh hydrodynamic conditions, brings significant challenges to the deployment and operation of marine energy devices. So a systems engineering approach, specificially speaking, optimizing energy capture, enhancing system integration, ensuring environmental adaptability, and strengthening lifecycle management, is necessary for tackling these challenges.

4.2.1. High-resilience system integration design

The core of deep-sea deployment is ensuring the reliability of the energy capture system under harsh environments, which relies on the co-design of entire system, range from the energy capture unit to the mooring and transmission system.

In low-flow-velocity environments, conventional lift-based turbines often struggle to achieve self-starting. To address this, a research team proposed a Ductless Archimedes Screw Turbine (DAST) which can achieve efficient self-starting under low-flow conditions after optimization [8]. Meanwhile, the adoption of an array configuration enhances system power output and operational reliability. Specifically, a counter-rotating DAST array can effectively increase the power coefficient while an optimized triangular array layout reduces reliance on yaw systems and exhibits directional

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fault tolerance. By combining fixed installation and passive yaw strategies, the system can better adapt to highly variable flow directions. Furthermore, the resilient design of deep-sea mooring systems and dynamic cables is equally critical. An optimized four-line mooring system has been shown to significantly improve platform stability and enhance energy capture efficiency.

4.2.2. Intelligent operation and maintenance with efficient verification

The high operational and maintenance costs in deep seas impose urgent demands for innovation in maintenance paradigms. The construction of high-fidelity digital twins and efficient verification tools is the fundament to achieving rational and cost-effective O&M.

A full-process test platform can serve as an alternative to traditional and expensive sea trials. By leveraging CFD-validated data and response surface methodologies to simulate turbine performance, it reduces costs and accelerates the R&D cycle. Siting precision is also critical. A "macro-micro" framework, which integrates macroscopic oceanographic data with microscopic CFD simulations, can optimize platform positioning to balance power output and stability [9]. Meanwhile, the integration of a U-Net model enables rapid flow field reconstruction, offering possibilities for dynamic site selection. Furthermore, a data-driven predictive maintenance closed loop which built upon the digital twin allows for real-time equipment monitoring, fault prediction and maintenance strategy optimization, can reduce lifecycle O&M costs effectively.

5. Conclusion

This article argues that marine energy has moved beyond early proof-of-concept phase and now is entering a commercialization breakthrough phase, where key challenges lie in reliability, cost and system integration. This research reveals the followings: tidal and wave energy technologies are at the forefront with successful megawatt-scale demonstrations proving their viability for continuous power generation; high-fidelity simulations and integrated land-sea verification accelerate technological development and mitigate R&D risks; the synergy of power smoothing and intelligent grid integration technologies ensures power quality and grid stability; and the resilient deployment-predictive operation and maintenance framework for deep-sea environments is essential for reducing lifecycle costs and enabling commercialization. This paper outlines technological advances, integration hurdles and commercialization pathways, providing a roadmap for researchers and valuable insights for engineering, investment and long-term planning.It should be realized that advancing marine energy is not only about adding a new energy source but about laying the engineering foundation to tap into the vast zero-carbon potential of the oceans and ensuring future energy and climate stability.

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